MICROMETEOROID AND ORBITAL DEBRIS IMPACT DAMAGE RECORDING SYSTEM

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ABSTRACT

The purpose of the Micrometeoroid and Orbital Debris (MMOD) Damage Recording System (DRS) project is to develop a reliable, mass and power efficient Thermal Protection System (TPS) impact detector to be integrated with manned and robotic spacecraft. The Columbia Space Shuttle accident in 2003 spurred an investigation that led to the requirement of an active impact monitoring system on the Shuttle Orbiter wing leading edge [1]. The Crew Exploration Vehicle (CEV) is also considering active MMOD detection systems for monitoring damage to the backshell TPS. Damage from MMOD impacts pose a substantial risk for the loss of crew for the currently planned CEV missions to ISS.

This paper details the development, fabrication, and testing of the DRS, a mass and power efficient solution for MMOD impact damage detection for TPS materials applied to future human rated reentry spacecraft. Test results have confirmed the DRS system as a viable MMOD impact damage recorder. Vehicle integration and further space environment testing remain critical steps in maturing to flight qualification. Future work will address these steps individually to advance the DRS development into a mature system.

1. INTRODUCTION

The Columbia Space Shuttle accident in 2003 has spurred the requirement for a Thermal Protection System (TPS) impact monitoring system. Presently, wireless impact monitoring sensors have been implemented within the leading edge of the Space Shuttles' wings to detect foam shed from the fuel tank during ascent [1]. Development of the shuttle's successor coupled with flexible, thin film electronic sensing technologies, has spurred interest in the development of impact monitoring systems that could be implemented for a variety of MMOD risk mitigation approaches in new vehicle human-rated vehicle design.

1.1 Micrometeoroid and Orbital Debris

Micrometeoroid and Orbital debris (MMOD) in the low Earth orbit (LEO) environment is made up of micro-meteoroids and man-made debris. The man-made debris consists mainly of fragmented rockets and satellites that have been left over from the over 50 years of space exploration. MMOD found in LEO have velocities averaging 10 km/s (22,000 mph), which can cause catastrophic damage to TPS or other spacecraft structures if impact occurs [2]. Risk from MMOD impact damage is a growing threat to operations in LEO as increased debris from man-made sources accumulates in a variety of orbits around the Earth.

MMOD having a diameter of greater than 10 cm can be monitored and tracked by ground systems. These larger MMOD objects can be avoided by maneuvring a spacecraft out of the projected MMOD path, causing little threat. Smaller MMOD, having a diameter of less than 1 mm, are generally not large enough to cause substantial TPS damage from hypervelocity impact. However, MMOD having a diameter of greater than 1 mm and less than 10 cm poses the greatest threat. This range of MMOD is hard to track by ground systems, but is large enough to cause serious damage to a spacecraft [2]. Thus, alternative means are being considered to mitigate the threat posed by MMOD that pose significant risk to manned spacecraft.

2. DAMAGE RECORDING SYSTEM

The Damage Recording System (DRS) achieves MMOD impact detection by utilization of three main components; the Embedded Damage Recorder (EDR) sensor, the Shock Micro (SMicro) sensor, and the custom designed Wireless Data Acquisition System (WDAS). These three components integrated together form one node of the DRS. Each node can employ up to three SMicro sensors and eight EDR sensors. The number of DRS nodes and the amount of sensors per node are a function of the area of the vehicle that needs to be monitored for MMOD impact damage.

When the DRS is integrated with a vehicle, each of its three components has a specific task. The SMicro sensors are the first line of detection. In the event of an impact the SMicro sensors trigger the WDAS to 'wake up' from its low power state. The WDAS then scans the EDR sensors to determine if critical damage has transpired. The data from the EDR sensors is then wirelessly transmitted by the WDAS to the health monitoring system of the vehicle.

2.1 Embedded Damage Recorder Sensor

The EDR sensor functions by mechanically storing any breaks in the network of copper traces in the flexible printed circuit board substrate. A continuity test determines whether electrical current flows through a copper trace sensing line by applying a voltage at one end and monitoring the other [3]. If there is high current flow through the substrate indicating low resistance, then the substrate is uniform throughout. If there is not current flow through the substrate during the continuity test a high resistance is returned, which indicates the presence of a fracture in the substrate. To use the principle of continuity as an impact detector, a uniform wire trace is placed in the area of potential impact. In the event of a penetration due to impact, the wire trace will be fractured causing a loss of continuity, which will then verify damage to the area in which the wire trace was located. The wire trace acts as a mechanical, non-volatile memory by permanently storing the impact damage data within its structure, making it attractive for damage detection and aiding potential visual inspection.

Detecting impact damage on large surfaces requires more than one wire trace. To meet this requirement, various copper wire trace impact grid geometries must be developed to give appropriate size and location, which depends upon critical damage criteria derived from the vehicle aeroshell design. When realizing the sensing grid, many wire traces must be laid out uniformly to cover the surface of the location on the aeroshell skin. Since each wire trace in the sensing grid requires continuity testing, it is more efficient to connect one end of each wire trace to a constant signal. Then the other end of the wire traces are monitored to verify whether they have been damaged due to an impact. Performing this test on each wire trace within the grid will then indicate the approximate size and location of the impact damage which is recorded by scanning through the wire traces that fail the continuity test.

Figure 1 is an example of impact damage on the sensor grid. The dark solid lines indicate intact wire traces, while the lighter dashed lines indicate a failed continuity test, representing a fracture in the wire trace.

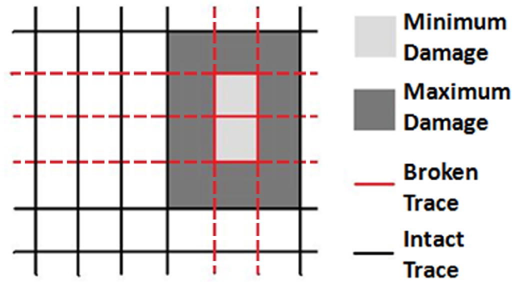

Fig. 1. Sensing Grid Impact Damage Example.

As you can see there are five broken wire traces. By analyzing where the broken wire traces intersect, the damage location can be determined and the damage diameter can be estimated. In Figure 1 the lighter squares in the sensing grid illustrate the minimum possible impact damage area that is indicated by the five broken wire traces, while the darker squares illustrate the maximum possible impact damage area.

Many EDR design cycles have led to an optimized sensor that meets the MMOD damage detection criteria (tailored to CEV requirements) while maintaining a very lightweight footprint. The optimized EDR sensor has been designated as the 2x2 Serpentine, which is shown in Figure 2.

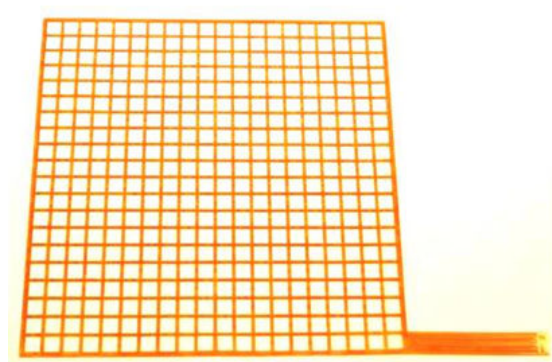

Fig. 2. 2x2 Serpentine EDR Sensor.

The 2x2 Serpentine EDR sensor displayed in Figure 2 employs four serpentine copper traces in a grid size of 20cm square, fabricated within a two-layer flexible printed circuit. The serpentine traces are spaced 1cm apart to maintain an impact detection resolution of 1cm, and are positioned in a 2x2 formation so that they form four 5cm square quadrants for damage location (Figure 3). The four serpentine traces have been labelled W, X, Y, and Z.

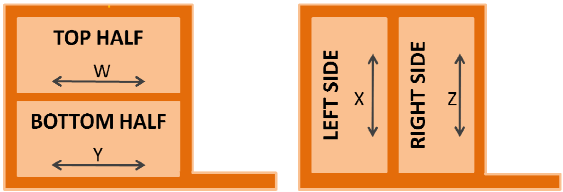

Fig. 3. Top (left) and Bottom (right) Layers of the 2x2 Serpentine EDR Sensor.

In order to appropriately denote the 2x2 Serpentine sensor, the layout of the left side and right side serpentine traces, are denoted as X and Z, which overlay the top half and bottom half serpentine traces, W and Y. This creates 4 detectable quadrants as seen in Figure 4. Damage to Q1 is realized by breaks in serpentine traces W and X, Q2 by W and Z, Q3 by Y and X, and Q4 by Y and Z.

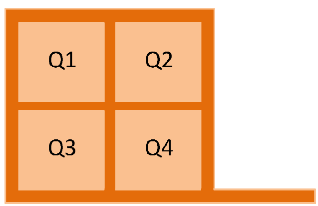

Fig. 4. Four Quadrants of the 2x2 Serpentine Sensor.

The 2x2 Serpentine EDR sensor is lightweight (3.01 grams), and is fabricated using flexible printed circuit board technology. Flexible circuits reduce the size and mass associated with rigid circuit board layout, along with making the circuit itself easily pliable [4]. Thin films composed of polyimide sheets, copper and an adhesive make up the layers of the sensor. The 2x2 serpentine EDR is less than 0.2 mm thick. Polyimide's demonstrated durability to the harsh environment found in LEO (resistance to atomic oxygen, thermal and chemical stability), combined with widespread use in flexible printed circuit board manufacturing make it ideally suited for use in this application [5]. The two layer design is comprised of a bottom polyimide layer, a lower copper layer, a middle polyimide layer, an upper copper layer and a top polyimide layer. [6].

As seen in Figure 2, the 2x2 Serpentine EDR sensor has been fabricated with cut-outs in between the copper traces in order to embed the sensor at the bondline between the TPS and the underlying carrier, This approach removes 80 percent of the polyimide sheet between the wire traces, greatly reduces the mass of the EDR sensor, and allows for minimal bondline integrity interference (Figure 5).

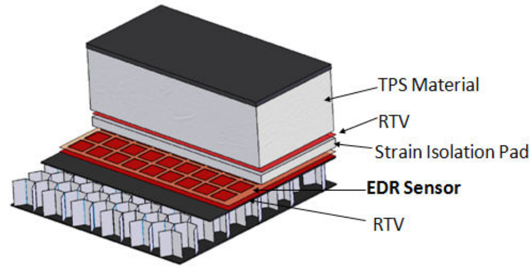

Fig. 5. 2x2 Serpentine EDR Sensor Placed at the Bondline in a TPS Stack.

2.2 Shock Micro Sensors

The SMicro sensor is manufactured by Signal Quest in New Hampshire, USA. In the event of a shock occurrence, the SMicro sensor produces a pulse to interrupt, or 'wake-up' a microcontroller. The sensor is fully passive, requires no signal conditioning, and operates with currents as low as 0.25µA. The SMicro sensor sensitivity can be manufactured between 20g and 2000g. The mass of the SMicro sensor is minimal at 0.6 grams, and the dimensions are 3.3 mm x 6.9 mm [7].

The SMicro sensor has been integrated in the DRS using a resistor pull-up circuit. The sensor is connected to the circuit ground and acts as an electrical short until a shock event occurs. During the shock event the sensor connection becomes an open circuit, and the pull-up resistor in the circuit becomes the path of least resistance, which then generates a pulse [7]. The SMicro sensor and its prototype interface can be seen in Figure 6. The attachment interface and placement still needs to be optimized.

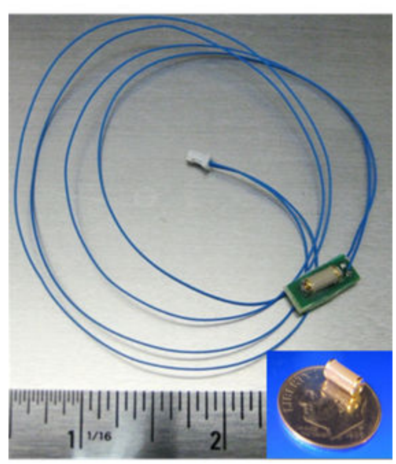

Fig. 6. SMicro Sensor and Prototype Interface.

2.3 Custom Wireless Data Acquisition System

Through many design iterations a custom WDAS was developed. The WDAS acts as an interface between the DRS sensors and the vehicle's health monitoring system. It is capable of monitoring up to three SMicros and eight 2x2 Serpentine EDRs. The WDAS employs a PIC16F microprocessor to run the impact damage monitoring algorithm. It then communicates any sensed critical damage data via a MaxStream XBee wireless transceiver.

The EDR and SMicro sensor support circuits located on the WDAS both utilize a resistor pull-up scheme to determine the state of the sensors. The SMicro sensor circuits are directly connected to the hardware interrupt pins of the microprocessor, enabling WDAS 'wake up' during the event of an impact. Given the large amount of EDR sensor signals, two 16:1 multiplexers are used to condense the signal inputs into the microprocessor.

The WDAS is extremely low power requiring 0.6mA during EDR sensor scanning, 52mA during wireless data transmission, and 5.5µA during low power sleep mode. Utilizing a 1Ah half size AA lithium battery, and a once per hour system check lasting approximately two seconds, the WDAS could survive remotely for a little over three years (assuming room temperature battery operation).

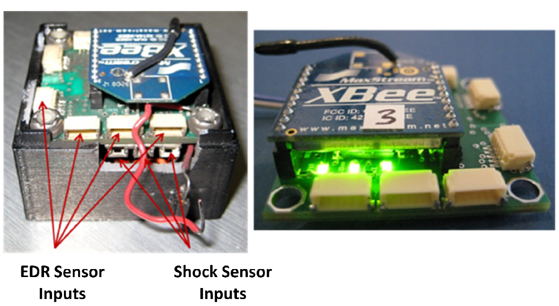

Fig. 7. WDAS (right) WDAS Mounted in Protective Housing for Testing at UDRI (left).

The WDAS including battery and protective housing can be seen on the left side of Figure 7, while the WDAS alone can be seen on the right side of Figure 7. Including the half size AA lithium battery and protective housing, the system weighs 59.4 grams, and its footprint is found to be 3.6 cm square by 3.2 cm tall.

2.4 Damage Recording System Software

The DRS impact detection algorithm is implemented within the microprocessor program code. To better understand the capabilities of the DRS system, the following algorithm was developed as a baseline for spacecraft integration testing. Unless prompted earlier by the SMicro hardware interrupt, once per hour the WDAS will wake-up from its low power sleep mode, and scan the EDR sensors for recorded damage. If recorded damage is not found, then the system quickly transmits 'No Damage Detected' and returns to its low power sleep mode for an hour until the next system scan. If recorded damage is found then the microprocessor calculates the proximity of the damage given the damaged traces, and then transmits 'Critical Damage Detected on Panel X, Quadrant X' alerting the health monitoring system of the problem. If the SMicro sensors are triggered due to impact, then the system will scan the EDR sensors as stated previously.

3. TESTING

Multiple iterations of the DRS system have been tested at White Sands Hypervelocity Impact Test Facility, University of Dayton Research Institute (UDRI), and on the International Space Station (ISS). This section will discuss the two most recent testing events, which includes the seven shot series at UDRI's Hypervelocity Impact Range, and the Materials on the International Space Station Experiment (MISSE).

3.1 University Dayton Research Institute

In August 2009 a seven shot test series was performed at the UDRI Hypervelocity Impact Range analyzing the DRS performance under flight-like parameters. Each of the seven shots was conducted using a two stage light gas gun that launched a projectile at a test article located in a vacuum chamber. The projectile used to simulate MMOD impact was approximately a 3 mm sphere made out of either aluminium or nylon. This sphere was shot at speeds of 7 km/s. Only the first shot of the test series will be described in depth to eliminate redundant results.

The first shot's test article, provided by Lockheed Martin, employed the 2x2 Serpentine EDR sensor at the bondline of a TPS stack-up. This test article stack-up was equal to what is illustrated in Figure 5. A SMirco sensor was placed on the side of the test article for initial impact detection. Both sensors were connected to the WDAS inside the vacuum chamber completing a DRS node. This setup can be seen in Figure 8. Outside the test chamber a health monitoring system mock-up was assembled to receive wireless data from the DRS node.

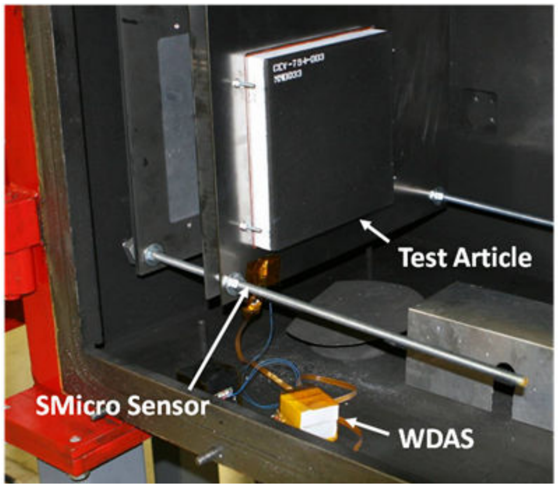

Fig. 8. UDRI Test Setup in the Two Stage Light Gas Gun Vacuum Chamber.

Results from the first shot indicated a successful DRS test. The system successfully detected the initial impact from the SMicro sensors which triggered the WDAS to scan the EDR sensor. This scan found a break in the W and Z traces indicating critical damage in quadrant Q2 of the EDR sensor. The WDAS then wirelessly alerted the health monitoring system that critical damage had been detected due to impact. Figure 9 shows the location of the impact due to the projectile, and a close up view of the damage cavity where it is possible to see one of the broken EDR traces.

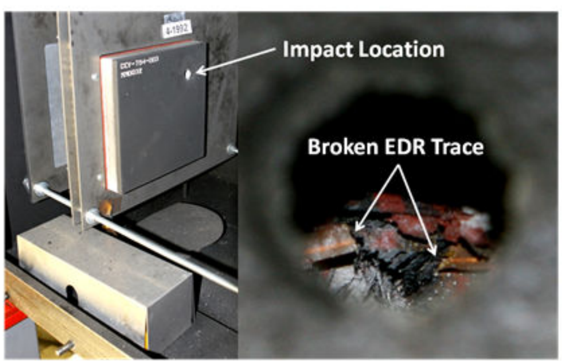

Fig. 9. First Shot Impact Location and Close Up View of Broken EDR Trace.

The next six shot's were identical in setup, except the projectile material was alternated using both aluminum and nylon. On all six hypervelocity shots the DRS correctly identified critical damage at the bondline of the TPS test articles, indicating that the DRS is a reliable device to determine MMOD impact damage. The details, pictures, and results of each test shot can be found in the UDRI HVI DRS August 2009 Test Report compiled by NASA Ames Research Center [8].

3.2 Materials International Space Station Experiment 7

MISSE is a test platform that allows flight qualification by investigation of the effects of long-term exposure to the harsh environment of space. Space introduces harsh environment parameters that include atomic oxygen, ultraviolet radiation, direct sunlight, ionizing radiation, and extremes of heat and cold, which all need to be accounted for in space component design [9]. MISSE is a collaborative effort between various NASA Centers, DoD and industry. Each collaborator contributes experiments to be conducted which are all confined to a small test package about the size and shape of a brief case. Once all of the experiments have been integrated into the test package, it is then launched to the ISS on-board the Space Shuttle and deployed to an attachment point external to ISS by the Shuttle crew. Once at the ISS a mission specialist performs an extravehicular activity (EVA) to mount the test package to the outside of the station. This configuration can be viewed in Figure 10. After on-orbit exposure (typically 9-18 months) the test package is removed through a second EVA and brought back to Earth for analysis.

Fig. 10. MISSE 6 On-Orbit Configuration.

On MISSE 7, currently on-orbit, an EDR sensor has been included in one of the NASA Ames experiments on the ISS velocity direction facing side of the test package. The EDR will be actively monitored by a data acquisition system, developed by NASA Ames, on board the test package. The test package is then linked to the ISS for data transfer, and once a day the data is downlinked to ground systems for analysis. A drawing of the NASA Ames experiment incorporating the EDR sensor is found in Figure 11. The MISSE 7 EDR sensor is a two layer serpentine sensor, with six vertical serpentine wire sensing traces, and six horizontal wire

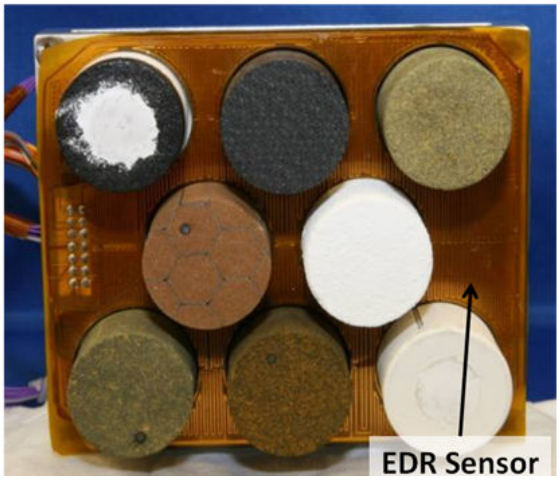

Fig. 11. EDR Sensor Integrated With NASA Ames Research Center MISSE 7 Experiment.

sensing traces. There are eight cutouts in the sensor to allow exposure to different TPS material plugs, along with four corner holes to allow for the fasteners between the top and bottom aluminum plates. The EDR is adhered to the top aluminum plate and soldered to a 14-pin header to allow connection of the 12 EDR sensor traces and the constant circuit ground signal. The chance of an impact to the EDR sensor is unlikely, but the evidence of long duration space exposure to the sensor is invaluable. Possible failures that will be evaluated upon the MISSE 7 test package return to Earth are EDR sensor delamination and degradation from the abrasive space environment. Also if any sensors pick up unexpected readings, the experiment will be examined for those particular instances.

4. FUTURE WORK

The DRS sensor's integration requires further development. One key designation that remains to be selected is a low risk location of spacecraft integration. To embed the EDR sensor at the bondline of the TPS, many risks must be analyzed and mitigated through ground and flight testing. The most important is a pull test to determine the bondline integrity with the embedded EDR sensor. It is imperative that the EDR sensor does not induce failure at this critical junction.

The WDAS needs to be structurally improved for use in extreme environments, and space qualified through a flight test. The protective housing and cable connectors need to be ruggedized in order to withstand vibration and shock. Connections between the WDAS and DRS sensors also will need to be ruggedized minimizing mass, while maximizing strength. The SMicro sensor's protective housing and interface needs to be developed further for system integration. The WDAS has been qualified for ground use by the UDRI 2009 test series. To be qualified for space flight the WDAS will have to undergo extreme environment flight testing, much like the EDR sensor on MISSE 7.

5. REFERENCES

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